

# Negative piezoresistivity in continuous carbon fiber epoxy-matrix composite

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**Abstract** The negative and positive piezoresistivity in continuous carbon fiber epoxy-matrix composite has been clarified. The negative piezoresistivity associated with the increase of the through-thickness resistivity upon longitudinal tension and decrease in the through-thickness resistivity upon longitudinal compression is practically attractive for strain sensing and is attributed to the decrease in the degree of contact between fibers of adjacent laminae upon longitudinal tension. This effect is stronger, more reversible and less prone to causing minor damage for the tension case than the compression case. The positive piezoresistivity associated with the longitudinal resistivity increasing upon longitudinal tension is negligibly weak, if any, independent of the number of laminae. The previously reported negative piezoresistivity associated with the longitudinal resistivity decreasing upon longitudinal tension does not occur for a commercially manufactured composite in which the fibers are well aligned.

## Introduction

### Piezoresistivity

Piezoresistivity is a phenomenon in which the electrical resistivity of a material changes with strain. It is practically useful for providing strain sensing through

electrical resistance measurement. Strain sensing is to be distinguished from damage sensing. Strain causes reversible effects, whereas damage causes irreversible effects.

The resistance  $R$  is related to the resistivity  $\rho$ , the length  $\ell$  in the direction of resistance measurement and the cross-sectional area  $A$  perpendicular to the direction of resistance measurement, i.e.,

$$R = \rho\ell/A \quad (1)$$

The fractional change in resistance is given by the equation

$$\delta R/R = \delta\rho/\rho + (\delta\ell/\ell)(1 - \nu_{12} - \nu_{13}), \quad (2)$$

where  $\nu_{12}$  and  $\nu_{13}$  are values of the Poisson ratio for the transverse and through-thickness strains respectively.

Positive piezoresistivity refers to the behavior in which the resistivity increases with increasing strain, i.e.,  $(\delta\rho/\rho)/(\delta\ell/\ell) > 0$ . Negative piezoresistivity refers to the behavior in which the resistivity decreases with increasing strain, i.e.,  $(\delta\rho/\rho)/(\delta\ell/\ell) < 0$ . Piezoresistivity is usually positive, because elongation tends to change the microstructure in such a way that the resistivity becomes larger in the direction of elongation. For example, a composite with an electrically non-conductive polymer matrix and a filler in the form of electrically conductive particles [1] or short fibers [2] tends to exhibit positive piezoresistivity, because the distance between adjacent particles increases upon elongation of the composite, thereby decreasing the chance of touching between the adjacent particles [1, 2]. However, negative piezoresistivity has been reported in polymer-matrix

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composites with continuous carbon fibers [3, 4] and with carbon nanofiber [5], and in semiconductors [6–8].

For the purpose of effective strain sensing, a large fractional change in resistance per unit strain is desired. Thus, the severity of piezoresistivity is commonly described in terms of gage factor, which is defined as the fractional change in resistance per unit strain. Equation 2 shows that the gage factor depends both on the fractional change in resistivity per unit strain and the Poisson ratio. A positive value of the gage factor does not necessarily mean that the piezoresistivity is positive, but a negative value of the gage factor necessarily means that the piezoresistivity is negative.

In order to attain a large fractional change in resistance at a particular strain, positive piezoresistivity is more desirable than negative piezoresistivity that exhibits the same magnitude of the fractional change in resistivity. When the strain is small, as is the case when the piezoresistive material is a stiff structural material, the fractional change in resistance is essentially equal to the fractional change in resistivity. Under this circumstance, positive and negative piezoresistivities are equally desirable for providing a large magnitude of the fractional change in resistance. From the viewpoint of the scientific origin, negative piezoresistivity is more intriguing than positive piezoresistivity.

#### Piezoresistivity in continuous carbon fiber polymer-matrix composites

Continuous carbon fiber polymer-matrix composites are important for lightweight structures such as aircraft because of their combination of high strength, high modulus of elasticity, and low density. Due to the strategic nature of aircraft and other aerospace structures, strain sensing is desirable.

Negative piezoresistivity has been reported in continuous carbon fiber polymer-matrix composites for various combinations of loading condition and resistance measurement configuration, as summarized below and referred to as negative piezoresistivity A, B, C and D. Positive piezoresistivity has also been reported such composites. The various forms of positive piezoresistivity are referred to below as positive piezoresistivity A, B, C and D.

Negative piezoresistivity A entails the resistivity in the through-thickness direction (i.e., the direction perpendicular to the laminae, which refer to the fiber layers) of the composite increasing upon uniaxial tension in the longitudinal direction [3, 4]. Due to the Poisson effect, the through-thickness direction undergoes shrinkage during the longitudinal tension. As a

result, the piezoresistivity in the through-thickness direction is negative. A similar phenomenon, referred to as negative piezoresistivity B, involves the resistivity in the transverse direction (i.e., the direction perpendicular to the fibers in the plane of the laminae) increasing upon longitudinal tension [9]. These two negative piezoresistive phenomena are due to the decrease in the extent of fiber–fiber contact in the direction of resistance measurement upon longitudinal tension.

Negative piezoresistivity C involves the longitudinal resistance decreasing upon compression in the through-thickness direction [10]. Due to the Poisson effect, slight extension occurs in the longitudinal direction, so the piezoresistivity is negative in the longitudinal direction. This effect is due to the squeezing of the fibers in the through-thickness direction causing the through-thickness resistivity to decrease. A decrease in the through-thickness resistivity helps conduction in the longitudinal direction, because it promotes the ability of the longitudinal current to detour from a longitudinal fiber to another in case of an imperfection in the first fiber.

Negative piezoresistivity A results in decrease in the extent of penetration of the electric current that is applied on the surface on the tension surface of a composite specimen under flexure, thereby causing the tension surface resistance to increase upon flexure [11]. As the through-thickness resistivity decreases upon longitudinal compression, negative piezoresistivity A results in increase in the extent of penetration of the electric current that is applied on the surface on the compression surface under flexure, thereby causing the compression surface resistance to decrease upon flexure [11].

Positive piezoresistivity A involve the contact electrical resistivity of the interlaminar interface decreasing upon compression in the through-thickness direction, due to the increase in proximity between the fibers of the adjacent laminae [12]. The contact electrical resistivity of the interlaminar interface relates to the volume resistivity in the through-thickness direction, since the through-thickness volume resistance is the sum of the contact resistance of each interlaminar interface and the through-thickness volume resistance of each lamina in the composite. The microstructure of the interlaminar interface affects the contact resistivity of the interface. As a result, the contact resistivity is highly sensitive to the strain [12].

Positive piezoresistivity A is in contrast to negative piezoresistivity A, which involves the through-thickness resistivity increasing upon longitudinal tension [3, 4]. Negative piezoresistivity A occurs because of the

adjacent laminae being not able to become closer to one another in the epoxy matrix in the absence of through-thickness compression; the longitudinal tension causes the fibers of adjacent laminae to have less chance of touching one another, thereby resulting in negative piezoresistivity in the through-thickness direction.

Negative piezoresistivity D involves the longitudinal resistivity decreasing upon uniaxial tension in the longitudinal direction [3, 4]. However, this phenomenon is not observed when the composite consists of only a single lamina; the piezoresistivity is weakly positive rather than being negative, whether surface sanding is conducted [9, 13] or not [14] prior to electrical contact application. This is referred to as positive piezoresistivity B. For composites with multiple laminae, negative piezoresistivity D is larger for composites that contain fibers that are less perfectly aligned during fabrication [3].

In general, the degree of alignment of the fibers in a composite depends on the details of the fabrication method. Due to the fact that the composites used in the prior work [3] were small-scale in-house manufactured rather than large-scale commercially manufactured, the degree of fiber alignment in these composites is relatively low, as indicated by a value of only  $10^2$ – $10^3$  for the ratio of the through-thickness resistivity to the longitudinal resistivity [15]. Therefore, this work is partly aimed at extending the prior work [3, 15] to a commercially manufactured composite for the purpose of assessing the piezoresistivity in the case of a composite with highly aligned fibers (with a value of  $10^5$  for the ratio of the through-thickness resistivity to the longitudinal resistivity [16]).

The volume resistance relates to the volume resistivity, whereas the surface resistance depends on the depth of current penetration. This depth can vary with the strain/stress, in addition to varying with the lamina lay-up configuration and the fiber volume fraction. Therefore, the volume resistance is a better attribute than the surface resistance for indicating the piezoresistive phenomenon. This work addresses the volume resistance.

The volume resistance is the measured resistance in prior work that reported negative piezoresistivity D [3, 4]. However, based on surface resistance measurement during longitudinal tension, it was reported that the negative piezoresistivity D is merely a consequence of not subjecting the specimen surface to sanding for the purpose of removing the surface matrix layer prior to application of electrical contacts and that surface sanding results in the piezoresistivity becoming weakly positive [9, 13]. This observation

[9, 13] is the same as positive piezoresistivity B, as explained below.

The initial surface resistance  $R_0$  prior to any loading is  $0.4 \Omega$  (Fig. 8 of Ref. 9) for a single-lamina composite (surface sanded) of length 30 mm between the voltage probes and of width 12 mm, whereas the corresponding value is  $0.8 \Omega$  (Fig. 14 of Ref. 9) for a six-lamina composite (also surface sanded) of length 70 mm between the voltage probes and also of width 12 mm [9]. Assuming that the volume resistivity in the longitudinal direction is the same for the single-lamina and six-lamina composites, and that the thickness of the latter is six times that of the former,  $R_0$  for the six-lamina composite should be  $0.2 \Omega$ , as obtained by simple calculation. This value is much smaller than the value of  $0.8 \Omega$  reported in Fig. 14 of Ref. 9. This difference means that the current penetration is small in the work associated with Fig. 14 of Ref. 9. If the current only penetrates through the thickness of the surface lamina, the six-lamina composite is electrically like a single-lamina composite. Based on the measured  $R_0$  of  $0.4 \Omega$  for the single-lamina composite with a distance of 30 mm between the voltage probes (Fig. 8 of Ref. 9), an  $R_0$  value of  $0.9 \Omega$  is obtained by simple calculation for the six-lamina composite (with only the surface lamina experiencing the current) with a distance of 70 mm between the voltage probes. The value of  $0.9 \Omega$  is close to the measured value of  $0.8 \Omega$  for the six-lamina composite. Thus, the measured  $R_0$  for the six-lamina composite is consistent with the fact that the electrical contacts are only on one side (rather than being perimetric, i.e., rather than being all the way around the perimeter of the specimen) and, as a consequence, the measured resistance is the surface resistance rather than the volume resistance. Due to the limited current penetration, the surface resistance is close to the volume resistance of the lamina that is in contact with the electrical contacts. As a result, the measured piezoresistivity is essentially that of a single lamina. Indeed, the gage factor of +2.6 for the six-lamina composite is close to that of +2.0 for the single-lamina composite [9].

In general, electrical resistance measurement can be done using the four-probe method or the two-probe method. The former involves four electrical contacts, the outer two of which are for passing current and the inner two of which are for voltage measurement. The latter involves only two electrical contacts, each of which is both for passing current and voltage measurement. The two-probe method gives a measured resistance that includes the contact resistances, whereas the four-probe method gives a measured resistance that does not include the contact resistance.

Thus, the resistance measured by using the two-probe method depends on the quality of the electrical contacts, whereas that measured by using the four-probe method essentially does not. As a consequence, change in quality of one or more electrical contacts (as it may occur during loading/unloading) affects the resistance measured by using the two-probe method much more than affecting the resistance measured by using the four-probe method. This work uses the four-probe method.

Based on volume resistance measurement on specimens that have not been surface sanded prior to electrical contact application, it has been reported that negative piezoresistivity  $C$  occurs when the four-probe method is used and positive piezoresistivity (referred to as positive piezoresistivity  $C$  and involving the longitudinal resistivity increasing upon longitudinal tension) occurs when the two-probe method is used [17]. Similarly, Angelidis et al. [18] observed positive piezoresistivity  $C$  when the two-probe method is used.

In case that the current contacts are not at the fiber ends (i.e., the ends of a specimen bar) but are around the sides of the fibers (i.e., the sides of a specimen bar), the four-probe method requires that the adjacent current and voltage probes be sufficiently far apart that the current is uniform throughout the thickness of the specimen in the region of resistance measurement. This uniformity is necessary for measurement of the volume resistance. Indeed, the current contacts are not at the fiber ends [9]. If the adjacent current and voltage probes are not sufficiently far apart, the current only penetrates the specimen to a limited thickness and the measured resistance (which is obtained under the assumption that the current penetrates the entire thickness of the specimen) is higher than the actual volume resistance. We found that, for a unidirectional eight-lamina composite (10 mm wide, 1.1 mm thick), the measured resistance decreases with increasing separation between the adjacent voltage and current probes, such that the measured resistance levels off at a separation of 40 mm for a specimen that has not been sanded at the surface prior to electrical contact application and 30 mm for a specimen that has been sanded at the surface prior to electrical contact application [19].

The distance between the adjacent current and voltage probes is about 3 mm in Ref. 9, but is at least 20 mm in Ref. 17. The small distance in Ref. 9 makes the current penetration limited, so that the measured resistance is too high. In addition, the small distance makes the adjacent current and voltage probes almost at the same position, so that the four-probe method used in Ref. 9 is close to the two-probe method.

Removal of the surface polymer reduces the measured resistance, even if the four-probe method is used [19]. The decrease in resistance between the adjacent current and voltage probes contributes to making the four-probe method used in Ref. 9 even closer to the two-probe method. The two-probe method gives positive piezoresistivity  $C$ , even when the four-probe method applied on the same material gives negative piezoresistivity  $C$  [17].

The gage factor is +3.0 for the eight-lamina unidirectional composite (without surface sanding) using the two-probe method, i.e., positive piezoresistivity  $C$  [17]. The corresponding gage factor is +2.6 for the surface sanded six-lamina unidirectional composite using the four-probe method, i.e., positive piezoresistivity  $B$  [9]. That these two values of the gage factor are close supports the notion that the particular four-probe method used in Ref. 9 approaches the two-probe method.

Study of the effect of surface sanding in Ref. 9 uses a six-lamina composite of fiber volume fraction 0.5 and thickness 1.5 mm. In contrast, Ref. 14 uses an eight-lamina composite of fiber volume fraction 0.58 (a value that is typical of composites that are used in practice) and thickness 1.1 mm. Hence, the matrix volume fraction and lamina thickness are larger for Ref. 9 than Ref. 14. As a consequence, the chance of fibers of one lamina to touch those of an adjacent lamina is relatively low for Ref. 9, as supported by the presence of a resin-rich interlaminar region depicted in Fig. 1 of Ref. 9. This would result in a relatively high through-thickness resistivity, which would make current penetration even more difficult.

Surface sanding has much less effect on the piezoresistive behavior or the resistance noise level, if the volume resistance (rather than the surface resistance) is measured [19]. Surface polymer removal does not mean that the electrical contact is improved, in contrast to the assumption made in Ref. 9. The surface polymer removal by sanding is a destructive process that alters the composite. Furthermore, it is a process that is undesirable and inconvenient in practice, since it can cause damage to the fibers at or near the surface (thereby degrading the mechanical properties of the composite), and it is labor-intensive and hard to control. Nevertheless, this work subjects the specimens to surface sanding prior to the application of the electrical contacts, for the purpose of basic characterization of the piezoresistivity.

The resistance in the transverse direction (i.e., with both resistance and stress in the transverse direction) increases with transverse strain/stress, with a gage factor of 2, as observed for a 32-laminate composite

using the four-probe method without removal of the surface polymer prior to the application of the electrical contacts [20]. In Fig. 10 of Ref. 9, the corresponding gage factor is +4.0 for a single-lamina composite that has been surface sanded. In spite of the difference in gage factor, the results in the transverse direction (with stress also in the transverse direction) are qualitatively similar for Ref. 9 and 20. This weak positive piezoresistivity, referred to as positive piezoresistivity D, is because the extent of contact between the fibers of adjacent tows in the same lamina is decreased upon tension in the transverse direction.

The summary provided above for the negative and positive piezoresistivity of carbon fiber epoxy-matrix composites shows that the effect depends on the degree of alignment of the fibers, the method of electrical resistance measurement (the two-probe method versus the four-probe method), the resistance attribute (the volume resistance versus the surface resistance), the method of electrical contact application (whether the surface of the specimen is sanded prior to electrical contact application), the method of strain application (direct straining in the direction of resistance measurement versus straining in the perpendicular direction and the involvement of the Poisson effect), and the direction of resistance measurement (longitudinal, transverse and through-thickness directions). The Appendix provides a glossary of the various forms of positive and negative piezoresistivity.

## Objectives

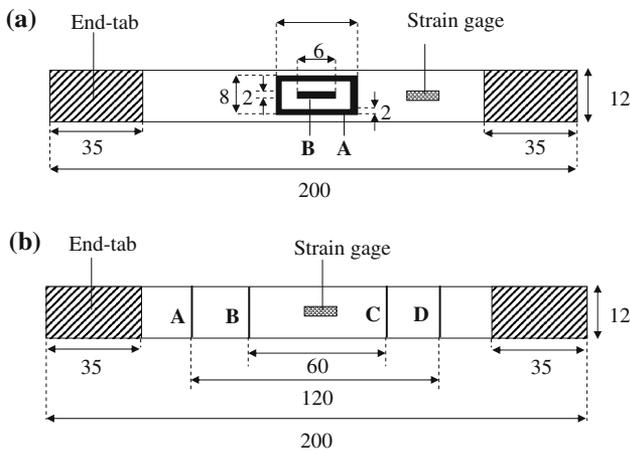
As suggested by the summary in ‘Piezoresistivity in continuous carbon fiber polymer-matrix composites’ it is necessary to find out the true and inherent piezoresistivity behavior of the composite itself and distinguish this behavior from behavior that is a consequence of the non-ideal method of testing. Thus, the first objective of this paper is to clarify the piezoresistive behavior of carbon fiber epoxy-matrix composite, with focus on negative piezoresistivity A, negative piezoresistivity D and positive piezoresistivity B. Negative piezoresistivity B is not addressed in this work because it is akin to negative piezoresistivity A. Furthermore, negative piezoresistivity B has less practical relevance than negative piezoresistivity A, because it is only applicable to unidirectional composites whereas negative piezoresistivity A is applicable to unidirectional and multidirectional composites. Positive piezoresistivity C is not addressed in this work, because it is an artefact resulting from the use of the two-probe method. Negative piezoresistivity C, positive piezoresistivity A and positive piezoresistivity D are not

addressed in this work because they do not require confirmation. The clarification in this work involves measurement of the longitudinal and through-thickness resistance of a commercially manufactured composite upon uniaxial tension and uniaxial compression, using the four-probe method, with surface sanding performed prior to electrical contact application. Due to the scientific interest and technological relevance associated with negative piezoresistivity, the second objective is to investigate the negative piezoresistivity in this composite material.

## Experimental methods

The composite was a commercially manufactured 24-lamina quasi-isotropic  $[0/45/90/-45]_{3s}$  laminate with IM7 carbon fiber (Hexcel Corp., PAN-based, intermediate modulus of 290 GPa, diameter 5  $\mu\text{m}$ , 12,000 fibers per tow) and 977-3 epoxy (CYCOM, toughened epoxy resin with a curing temperature of 177  $^{\circ}\text{C}$ ). The piezoresistivity characterization involved subjecting a composite laminate specimen of size  $200 \times 12 \times 3.2$  mm to repeated uniaxial tension and uniaxial compression at progressively increasing stress amplitudes of  $x$ ,  $-x$ ,  $2x$ ,  $-2x$ ,  $3x$ ,  $-3x$ ,  $4x$  and  $-4x$ , where  $x = 5.8$  MPa, using a screw-action mechanical testing system. Positive stress is tensile, whereas negative stress is compressive. Three loading cycles were carried out at each stress amplitude. All stress amplitudes were within the elastic regime.

The DC resistance was measured using a resistance meter (Keithley Model 2002) and the four-probe method. The through-thickness volume resistance was measured using the configuration of Fig. 1a and the longitudinal volume resistance was measured using the configuration of Fig. 1b. In the configuration of Fig. 1a, each of the two current contacts is in the form of an open rectangle at the center of the specimen, while each of the two voltage contacts is in the form of a solid small rectangle centered within the open rectangle mentioned above. Each of the two opposite surfaces has a current contact and a voltage contact, such that the corresponding contacts on the two surfaces are directly opposite each other. In the configuration of Fig. 1b, each of the four electrical contacts is around the whole perimeter of the specimen in a plane that is perpendicular to the length of the specimen. All contacts in Fig. 1 were in the form of silver paint, which was applied after light sanding of the specimen surface to remove the surface matrix layer. The longitudinal strain was measured by using a metallic strain gage that had been adhesively attached to a surface along the length of the specimen, as shown in both Fig. 1a and



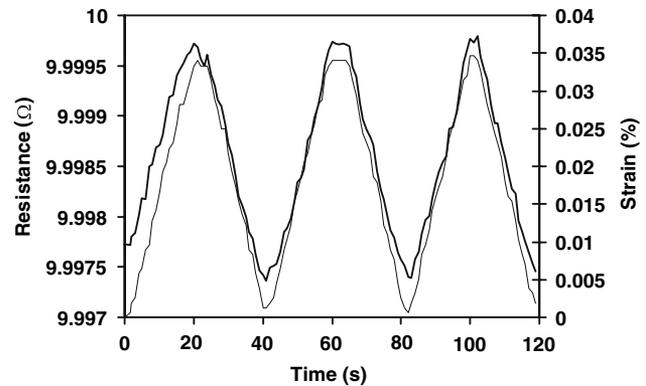
**Fig. 1** Electrical contact configuration for piezoresistivity evaluation. (a) Configuration for measurement of the through-thickness resistance. (b) Configuration for measurement of the longitudinal resistance. All dimensions are in mm

1b. At least two specimens were tested for each of the configurations in Fig. 1 in order to show the general reproducibility of the results, though the data for a single specimen are presented for each configuration.

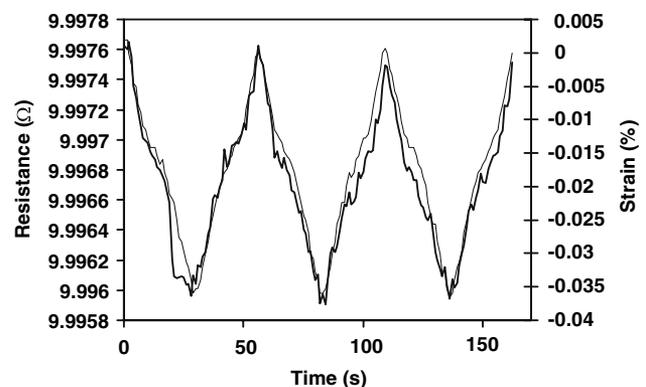
## Results and discussion

The initial electrical resistance (value prior to any loading) is  $0.167 \Omega$  in the longitudinal direction and  $10.00 \Omega$  in the through-thickness direction. The initial resistivity is  $0.0107 \Omega \text{ cm}$  in the longitudinal direction. Due to the unclear extent of longitudinal current spreading in Fig. 1a, only the lower bound of the through-thickness resistivity can be determined. The lower bound, as obtained by assuming no outward current spreading, is  $79.92 \Omega \cdot \text{cm}$ . The true through-thickness resistivity, as separately measured in a specimen of size  $22 \times 10 \times 3.2 \text{ mm}$  using the four-probe method and silver paint electrical contacts, is  $600 \Omega \text{ cm}$  [16].

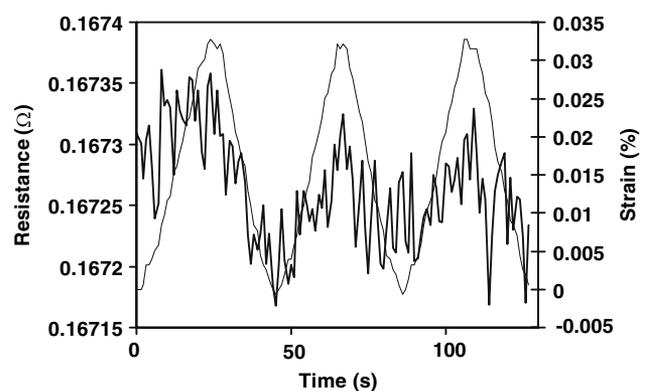
Figures 2–5 respectively show the through-thickness resistance during repeated tension, the through-thickness resistance during repeated compression, the longitudinal resistance during repeated tension, and the longitudinal resistance during repeated compression, all at a stress amplitude magnitude of about 17.4 MPa. The through-thickness resistance increases reversibly upon tension and decreases reversibly upon compression, whereas the longitudinal resistance slightly increases upon tension and slightly decreases upon compression. Thus, the effect of loading on the longitudinal resistance is weak compared to that on the through-thickness resistance. At a stress amplitude of



**Fig. 2** Variation of the through-thickness resistance (thick curve) with time and of the strain (thin curve) with time during repeated longitudinal tension at a fixed stress amplitude of 17.5 MPa

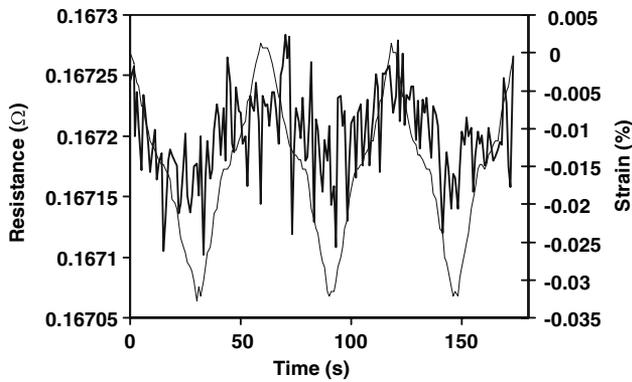


**Fig. 3** Variation of the through-thickness resistance (thick curve) with time and of the strain (thin curve) with time during repeated longitudinal compression at a fixed stress amplitude of 17.4 MPa



**Fig. 4** Variation of the longitudinal resistance (thick curve) with time and of the strain (thin curve) with time during repeated longitudinal tension at a fixed stress amplitude of 17.4 MPa

11.8 MPa or below, the effect of loading on the longitudinal resistance is negligibly small, while that on the through-thickness resistance remains clear.



**Fig. 5** Variation of the longitudinal resistance (thick curve) with time and of the strain (thin curve) with time during repeated longitudinal compression at a fixed stress amplitude of 17.3 MPa

Table 1 shows the fractional change in resistance per unit longitudinal strain. This quantity is the longitudinal gage factor in case of the longitudinal resistance, for which the value is around 2, indicating that the piezoresistivity is negligibly weak, i.e., the change in resistance is essentially all due to dimensional change rather than resistivity change.

Due to the Poisson effect, the through-thickness dimension necessarily decreases upon longitudinal strain. Therefore, the fractional change in through-thickness resistance per unit through-thickness strain is negative, indicating negative piezoresistivity. Though the fractional change in through-thickness resistance per unit longitudinal strain is smaller than that in longitudinal resistance per unit longitudinal strain, as shown in Table 1, the negative piezoresistivity in the through-thickness direction is actually much stronger than the negligible piezoresistivity in the longitudinal direction. If a Poisson ratio of 0.3 [15] is assumed for the through-thickness strain, the through-thickness gage factor ranges from  $-1.8$  to  $-2.7$  for tension and from  $-1.2$  to  $-1.9$  for compression.

Table 1 also shows that the negative piezoresistivity becomes more strongly negative as the tensile strain amplitude increases and becomes less strongly negative

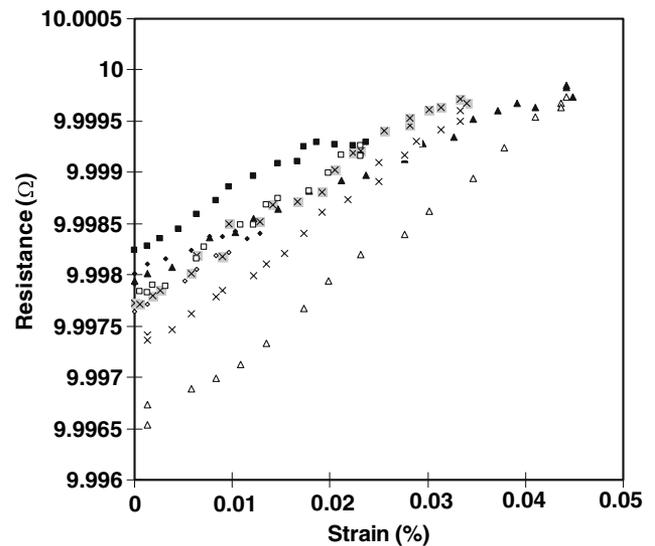
**Table 1** Fractional change in longitudinal and through-thickness resistance per unit longitudinal strain

Stress amplitude (MPa)	Longitudinal		Through-thickness	
	Tension	Compression	Tension	Compression
5.9	*	*	0.55	0.56
11.8	*	*	0.60	0.49
17.4	2.5	2.1	0.68	0.44
23.4	2.1	2.2	0.82	0.35

\* The resistance change is too small or too noisy to be measured

as the compressive strain amplitude increases. This trend is because the degree of fiber–fiber contact in the through-thickness direction decreases as the tensile stress increases throughout the range of stress investigated, whereas the incremental increase of this degree decreases as the compressive stress amplitude increases. In other words, once the degree of fiber–fiber contact in the through-thickness direction has increased upon longitudinal compression to a certain degree, further increase becomes more difficult, due to the geometric hindrance associated with the wavy fibers of adjacent laminae becoming very close together locally. Such hindrance does not occur during longitudinal tension. As a consequence, the negative piezoresistivity is stronger under longitudinal tension than longitudinal compression

Figure 6 shows the variation of the through-thickness resistance with strain during the first tensile loading cycle for each of four strain amplitudes. The slope of the curve is similar for all four-strain amplitudes. At the same strain, the resistance during loading is higher than that during unloading. This means that there is a small degree of irreversible resistance decrease after a loading cycle. This irreversible effect is strongest at the highest strain amplitude. It is attributed to an irreversible change in the microstructure of the interlaminar interface. This microstructural change is probably in the form of an increase in the degree of contact between fibers of adjacent laminae. In other

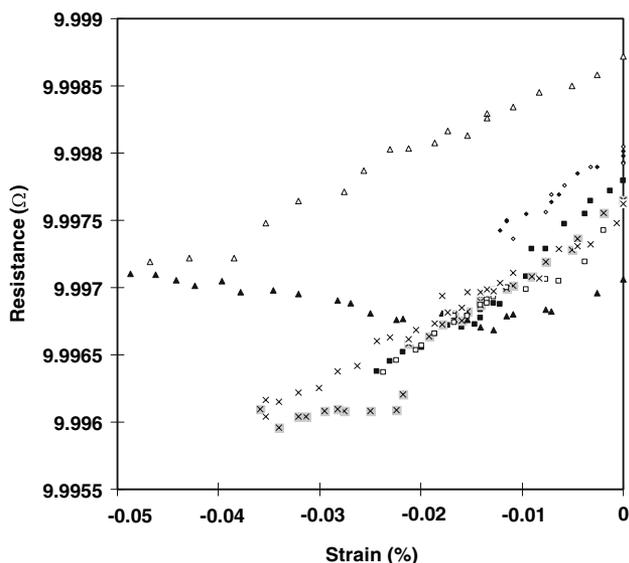


**Fig. 6** Variation of the through-thickness resistance with strain during the first cycle of tensile loading and subsequent unloading for four stress amplitudes. ◆ 5.9 MPa loading, ■ 11.7 MPa loading, × 17.5 MPa loading, ▲ 23.3 MPa loading, ◇ 5.9 MPa unloading, □ 11.7 MPa unloading, × 17.5 MPa unloading, △ 23.3 MPa unloading

words, the change in the degree of contact during a loading cycle disturbs the fiber arrangement slightly, thereby causing the degree of fiber contact to be higher at the end of a cycle than that before the cycle begins.

Figure 7 shows the variation of the through-thickness resistance with strain during the first compressive loading cycle for each of four strain amplitudes. For a strain amplitude of 0.0359% (stress amplitude of 17.4 MPa) or above, the resistance is higher during unloading than that during loading at the same strain. This effect is particularly severe at the strain amplitude of 0.0487% (stress amplitude of 23.5 MPa). It is attributed to minor damage (akin to delamination or its precursor) that occurs upon development of excessive local proximity between fibers of adjacent laminae. This effect is consistent with the decrease in the magnitude of the through-thickness gage factor as the compressive strain amplitude increases (Table 1).

This work confirms that negative piezoresistivity A is true. Furthermore, it shows that negative piezoresistivity A occurs both during longitudinal tension and longitudinal compression, though the effect is stronger, more reversible and less prone to causing minor damage for the tension case than the compression case. Negative piezoresistivity A is consistent with the prior report of the increase of the tension surface resistance and decrease of the compression surface resistance upon flexure [11].



**Fig. 7** Variation of the through-thickness resistance with strain during the first cycle of compressive loading and subsequent unloading for four stress amplitudes. The legend is shown below: ◆ 5.9 MPa loading, ■ 11.8 MPa loading, × 17.4 MPa loading, ▲ 23.5 MPa loading, ◇ 5.9 MPa unloading, □ 11.8 MPa unloading, × 17.4 MPa unloading, △ 23.5 MPa unloading

Negative piezoresistivity A confirmed in this work is weaker than that reported before for composites with less aligned fibers [3, 4]. This is consistent with the notion that this effect is due to the decrease in the degree of contact between fibers of adjacent laminae during longitudinal tension. When the degree of fiber alignment prior to any loading is high (as for the commercially manufactured composite of this work), the change in the degree of contact upon longitudinal tension is expected to be low compared to the case in which the degree of fiber alignment prior to loading is low (as for the in-house manufactured composite of prior work [3, 4]).

This work shows that negative piezoresistivity D does not occur for a commercially manufactured composite in which the fibers are well aligned. That it does not occur for a composite with well aligned fibers is consistent with the prior report that this effect diminishes with increasing alignment of the fibers [3, 4]. It is also consistent with the prior report that this effect is absent in a single-lamina composite [14].

This work confirms that positive piezoresistivity B is very weak, if any. Along with prior work [9, 14], it shows that positive piezoresistivity B is very weak, whether the composite consists of one or more laminae and whether or not surface sanding is conducted prior to electrical contact application. Due to the weakness of positive piezoresistivity B, this effect is not practically attractive for strain sensing.

Negative piezoresistivity A is strong, particularly in the case of longitudinal tension. The application of negative piezoresistivity A to the surface resistance during flexure is particularly attractive for practical flexural strain sensing [11].

## Conclusion

The negative and positive piezoresistivity in continuous carbon fiber epoxy-matrix composite, as previously reported by various researchers, has been clarified. Negative piezoresistivity A (first reported by Chung et al. in 1998 [3, 4]) is true and occurs both during longitudinal tension and longitudinal compression, though the effect is stronger, more reversible and less prone to causing minor damage for the tension case than the compression case, as found in this work. Negative piezoresistivity A is practically attractive for strain sensing and is attributed to the decrease in the degree of contact between fibers of adjacent laminae upon longitudinal tension.

Negative piezoresistivity D (first reported by Chung et al. in 1998 [3, 4]) does not occur for a commercially

manufactured composite in which the fibers are well aligned, as found in this work. Positive piezoresistivity B (first reported by Todoroki and Yoshida [9] and Chung et al. [14] in 2004), is negligibly weak, if any, independent of the number of laminae, as shown in this work.

### Appendix: Glossary

**Negative piezoresistivity A:** the resistivity in the through-thickness direction increasing upon uniaxial tension in the longitudinal direction.

**Negative piezoresistivity B:** the resistivity in the transverse direction decreasing upon uniaxial tension in the longitudinal direction.

**Negative piezoresistivity C:** the longitudinal resistance decreasing upon compression in the through-thickness direction.

**Negative piezoresistivity D:** the longitudinal resistivity decreasing upon uniaxial tension in the longitudinal direction.

**Positive piezoresistivity A:** the contact electrical resistivity of the interlaminar interface decreasing upon compression in the through-thickness direction.

**Positive piezoresistivity B:** the longitudinal resistivity increasing upon uniaxial tension in the longitudinal direction.

**Positive piezoresistivity C:** the longitudinal resistivity increasing upon longitudinal tension when the two-probe method is used.

**Positive piezoresistivity D:** the resistance in the transverse direction increasing with transverse strain/stress.

### References

1. Grimaldi C, Maeder T, Ryser P, Strassler S (2003) *Phys Rev B* 67:014205/1
2. Wen S, Chung DDL (2005) *J Mater Sci* 40:3897
3. Wang X, Fu X, Chung DDL (1998) *J Mater Res* 13:3081
4. Wang X, Chung DDL (1998) *Composites: Part B* 29B:63
5. Arlen M, Koerner H, Taylor BE, Alexander MD, Vaia R (2006) Abstracts of Papers, 231st ACS National Meeting, Atlanta, GA, USA, March 26–30, POLY-357, American Chemical Society, Washington D.C
6. Eickhoff M, Ambacher O, Krotz G, Stutzmann M (2001) *J Appl Phys* 90:3383
7. Pavlov AN, Raevskii IP (2002) *Phys Solid State (Translation of Fizika Tverdogo Tela (Sankt-Peterburg))* 44:1748
8. Morten B, Taroni A (1975) *Lett Nuovo Cimento Soc Italiana Fisica* 14:305
9. Todoroki A, Yoshida J (2004) *JSME Int J A* 47:357
10. Leong C, Wang S, Chung DDL (2006) *J Mater Sci* 41:2877
11. Wang S, Chung DDL (2006) *Carbon* 44:2739
12. Wang S, Kowalik DP, Chung DDL (2004) *Smart Mater Struct* 13:562
13. Todoroki A, Yoshida J (2005) *Key Eng Mater* 297–300(Pt. 1, *Advances in Fracture and Strength*):610
14. Gordon DA, Wang S, Chung DDL (2004) *Composite Interfaces* 11:95
15. Wang X (1997) PhD dissertation, State University of New York at Buffalo
16. Wang S, Chung DDL, Chung JH (2005) *J Mater Sci* 40:6463
17. Wang S, Chung DDL (2000) *Polym Compos* 21:13
18. Angelidis N, Khemiri N, Irving PR (2002) In: Balagcas DL (ed) *Proc first European workshop structural health monitoring 2002*, DEStech Publication, Lansacter, Pennsylvania, USA, pp 477–484
19. Wang S, Chung DDL unpublished result
20. Wang X, Chung DDL (1998) *Composite Interfaces* 5:191